

## RESEARCH ARTICLE OPEN ACCESS

# Geomorphic Responses to Post-Grazing Recovery and Stream Restoration in Semiarid Grassland Streams

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**Correspondence:** Ellen Wohl ([ellen.wohl@colostate.edu](mailto:ellen.wohl@colostate.edu))**Received:** 11 November 2025 | **Revised:** 15 January 2026 | **Accepted:** 18 February 2026**Keywords:** erosion | grazing | Great Plains | low-tech process-based restoration | stream restoration

## ABSTRACT

Semiarid grassland streams are sensitive to land use, climate, extreme discharges, and internal geomorphic thresholds that drive episodic erosion. Rooted in a process-based philosophy and commonly applied to historically wood-rich, beaver-modified systems, low-tech process-based restoration using structures is increasingly being extended to other geomorphic settings, including grasslands. In these wood-poor systems with fine-grained substrate, channel adjustment depends primarily on subsurface soil piping and asynchronous responses to changing boundary conditions. We evaluate post-grazing recovery and structural restoration outcomes at transect-to-landscape scales in southeastern Colorado. Following grazing cessation, soil compaction decreased after roughly a decade of rest, as indicated by a multivariate linear regression analysis of 238 bulk density samples. In contrast, visible above-ground upland vegetation recovers on timescales longer than the observation window ( $> 10$  years), based on analyses of growing-season composite Landsat imagery from 2013 to 2024. Logistic regression models indicate that the performance of restoration structures depends strongly on drainage area, slope, local vegetation cover, and the recency of large-scale commercial grazing. In total, only  $\sim 30\%$  of the 92 in-channel structures evaluated (mostly  $\leq 4$  years old) were both intact and produced visible geomorphic change. Structures in piping-dominated headwaters remained intact but rarely trapped sediment, whereas those in larger catchments were more likely to initiate local geomorphic change, despite having higher odds of destruction during peak flows. These findings highlight the need to match restoration strategies with the geomorphic processes driving channel adjustment and call into question the extent to which commonly implemented structure-based interventions in grassland systems are truly process-based.

## 1 | Introduction

### 1.1 | Semiarid Grassland Streams

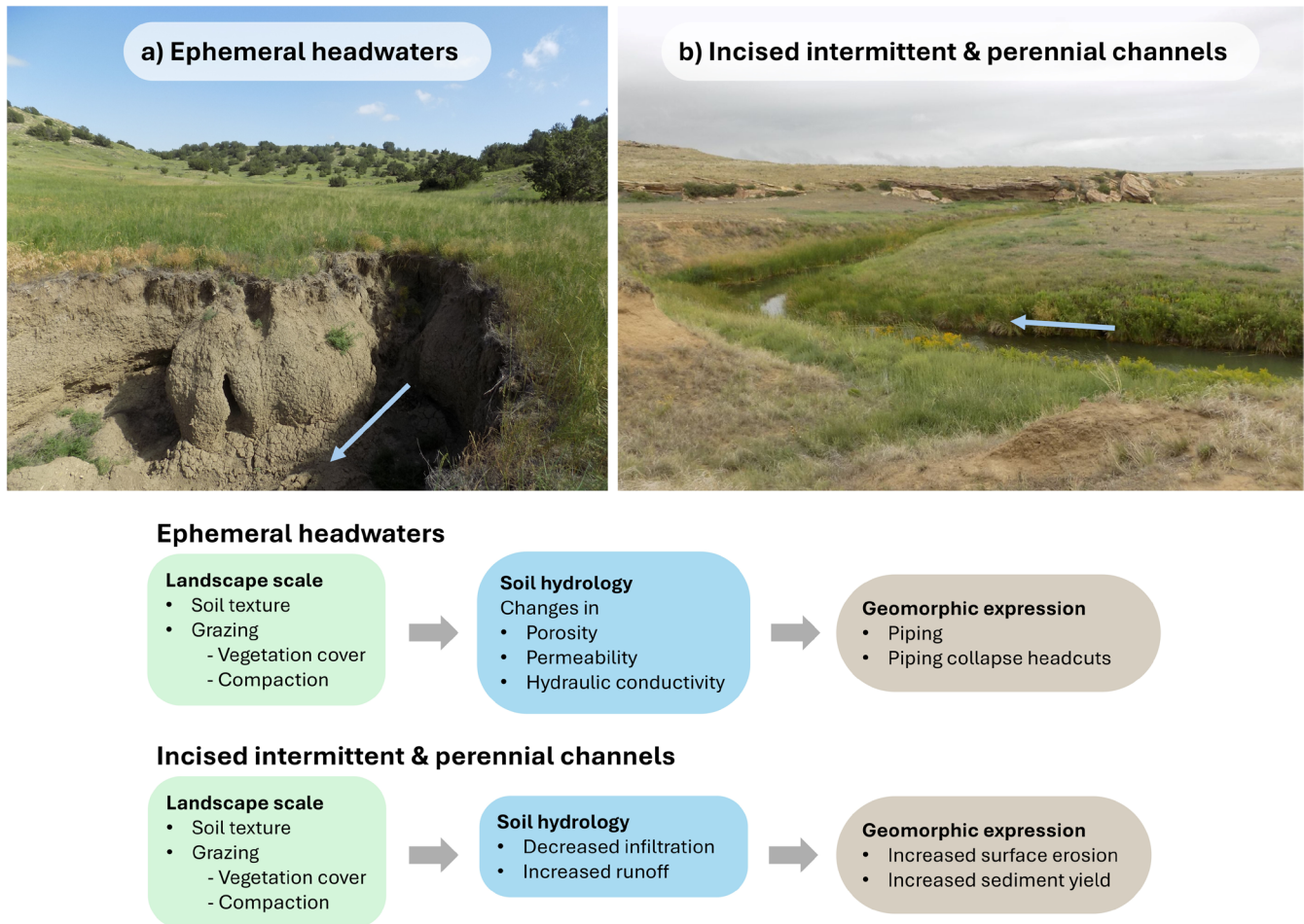
Grasslands cover roughly 40% of Earth's terrestrial surface and support extensive river networks that respond sensitively to both natural and human disturbances (Blair et al. 2014). In southeastern Colorado, the Southern Plains Land Trust (SPLT) has been restoring grassland streams in the semiarid Mud Creek and Rule Creek catchments since 2013. SPLT manages much of the upper Mud Creek catchment within its Heartland Ranch

Preserve, which encompasses ephemeral headwater streams upstream and incised intermittent and perennial reaches downstream. Within the Rule Creek catchment, streams in SPLT's Raven's Nest Preserve are generally representative of the latter category. Both Mud Creek and Rule Creek ultimately drain to the Arkansas River.

The diversity of hillslope and fluvial geomorphic processes across semiarid grassland streams lends itself to two distinct channel process domains (Figure 1a,b), as exemplified by channels on the SPLT preserves. The two process domains identified

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**FIGURE 1** | Key processes and drivers shaping channel morphology and landscape evolution in semiarid plains systems for (a) the ephemeral headwaters and (b) incised intermittent and perennial channels. Primary flow direction shown in blue. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.2702)]

within SPLT's preserves—ephemeral headwaters and incised channels—are widely observed across the Great Plains and other semiarid grasslands.

A third process domain is represented by large rivers draining grassland regions, including the Arkansas, Platte, and Missouri Rivers in North America. These perennial rivers historically had a braided planform, but they are now profoundly modified by large-scale channel engineering, flow regulation, extensive changes in land cover, groundwater pumping and irrigation return flows, and are not the focus of this study (Nadler and Schumm 1981; Johnson 1994; Williams 1978).

### 1.1.1 | Ephemeral Headwaters: Piping Collapse Networks

The first process domain consists of ephemeral headwaters, where steeper channels experience episodic surface flow, often emerging from the outlets of soil piping networks, and piping collapse dominates channel initiation. Piping occurs when infiltrating water concentrates into subsurface macropores, and erosion around these pores enlarges them into subsurface “pipes” (Bryan and Jones 1997; Barendregt and Ongley 1977). When piping conduits collapse, they form amphitheater-shaped subsidence features at the surface, often with visible macropore

conduits in the headcut wall (Figure 1a). Piping is a known driver of subsurface erosion throughout all major hydroclimatic regions (Bryan and Jones 1997). Studies of gully initiation spanning diverse sites have shown that subsurface erosion—specifically piping—is often a significant, even dominant, contributor to gully development (Bocco 1991; Higgins 1990; Dardis and Beckedahl 1988; Swanson et al. 1989; Verachtert et al. 2010). Anthropogenic land use, through its impacts on vegetation cover and soil compaction, may alter infiltration and piping processes (Floyd 1974).

At SPLT, field evidence such as amphitheater-shaped headcuts with no upstream signs of surface flow suggests that piping processes have heavily influenced channel morphology in the headwaters of Mud Creek and Rule Creek. The collapse of piping networks may limit the ability of surface erosion control structures to address headcut erosion in the ephemeral headwaters process domain since piping is a subsurface process.

### 1.1.2 | Intermittent and Perennial Channels: Arroyo Incision

The second process domain consists of intermittent to perennial arroyo channels, which may have originated through piping, surface erosion, or some combination of the two but

are now shaped by surface flows that both erode and deposit sediment. Arroyos are defined here as incised semiarid channels with steep banks that disconnect flow from adjacent alluvial surfaces. Many channels within the Mud and Rule Creek catchments can be described as arroyos. The causes of arroyo incision in semiarid landscapes have been highly debated within geomorphology since at least the 1880s. This body of work suggests many possible explanations for rapid arroyo incision, generally focused on the “cows versus climate” debate (Aby 2017).

Early works on arroyo incision investigated decadal scale incision and aggradation in the arid to semiarid American Southwest (Bryan 1928; Burkhart 1966). These studies focused on grazing as a driver of downcutting via changes in riparian vegetation, bank stability, compaction, and decreased infiltration (Trimble and Mendel 1995). They also noted that vegetation cover may control a threshold response such that areas with low vegetation cover (<40%) are especially vulnerable to increases in surface erosion due to grazing (Trimble and Mendel 1995; Zöbisch 1993; Graf 1979). Similarly, Tucker et al. (2006) and Gellis et al. (1991) observed that vegetation conditions greatly influence arroyo formation and stabilization processes.

As research into arroyo development progressed, geomorphologists also began to examine climatic shifts and extreme events as possible explanations for decadal- to century-scale cycles of alternating incision and aggradation in dryland channels (Richardson 1945; Leopold 1951; Langbein and Schumm 1958; Hereford 2002; Perignon et al. 2013). More broadly, studies by Schumm and Hadley (1957), Schumm and Parker (1973), Schumm (1975), Patton and Schumm (1975) and Gellis et al. (1991) argued that arroyo incision is an inherent and recurring process in semiarid drainages, with episodic trenching occurring throughout the Quaternary as an asynchronous, complex response to base level changes and the crossing of geomorphic thresholds.

At a fundamental level, periodic arroyo incision should be understood as a natural component of semiarid geomorphic systems that occurred in the Western United States prior to European settlement and associated changes in land cover, rather than as a strictly detrimental or anthropogenic disturbance. However, it is important to recognize the additional geomorphic impacts caused by cattle grazing, and to consider the potential for landscape response following cattle removal at SPLT.

## 1.2 | Restoration of Semiarid Grassland Streams

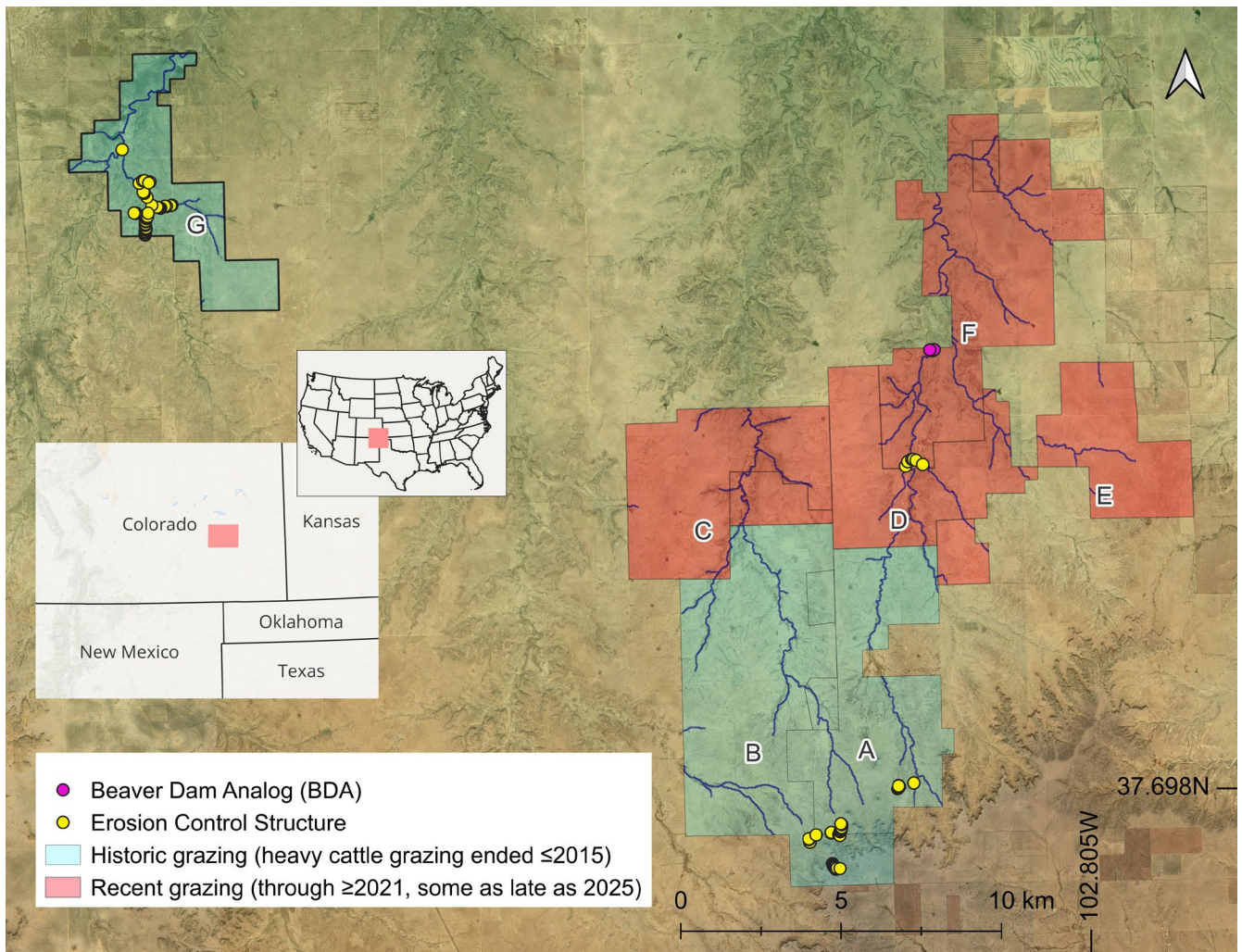
Stream restoration is a multi-billion-dollar global industry (Bergstrom and Loomis 2017; Bernhardt et al. 2005), yet only a small fraction (~10%) of projects have historically received any post-installation assessment or monitoring. Beechie et al. (2010) advocated for process-based restoration focused on restoring underlying geomorphic processes rather than simply constructing desired channel forms. Although process-based approaches have gained prominence, many restoration projects still fail to fully meet these principles. Most stream restoration projects lack long-term monitoring, particularly those in semiarid grassland streams, which have received little formal research focus.

More recently, low-tech process-based restoration (LTPBR) has gained popularity among practitioners (Scamardo et al. 2025). LTPBR builds on the principles of process-based restoration but emphasizes that structures should have a low unit cost and use locally sourced materials. Natural Infrastructure in Dryland Streams (NIDS) represents a formalized application of LTPBR principles developed specifically for arid and semiarid river corridors and wetlands. The NIDS framework describes how beaver-engineered and anthropogenic structures built from sediment, rock, wood, and other organic material can enhance dryland stream functionality (Norman et al. 2022; Figures 3–6). A Natural Resources Conservation Service (NRCS)-approved publication recommends low-tech surface erosion control structures for headcuts that are formed through subsurface-driven erosion. This approach risks mismatching treatment to underlying processes and could be problematic if applied broadly (Maestas et al. 2018). As emphasized by Wohl et al. (2024), the local geomorphic context and processes operating on a river system fundamentally control restoration outcomes.

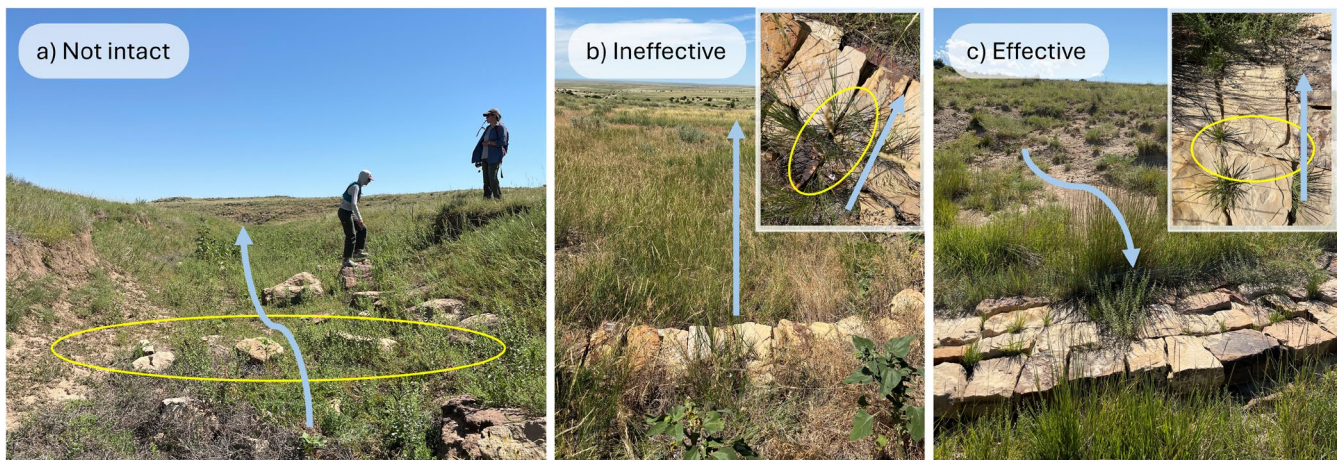
SPLT has installed over a hundred LTPBR and NIDS structures since 2013 to prevent surface erosion, enhance surface and subsurface water storage, create habitat, and meet other goals. Many are Zeedyk structures, a specific set of hand-built, anthropogenic NIDS restoration features installed following Zeedyk and Jansens (2009). Zeedyk structures are commonly small rock structures, oriented perpendicular to flow (Figure 3), though some designs incorporate wood, straw, and fabric. Numerous studies summarized by Scamardo et al. (2025) have evaluated geomorphic, hydrologic, and ecological outcomes of LTPBR, but long-term (3+ year) assessments remain rare, especially in shortgrass prairie systems.

Restoration efforts prior to LTPBR emphasize approaches such as the mechanical destruction of piping networks through “ripping” (Floyd 1974). However, this was only temporarily effective at preventing further subsurface erosion. Landscape-scale treatments were more effective: grazing management that allowed for dense vegetation cover helped retain water and prevented the desiccation cracks that rapidly feed macropores and piping networks (Floyd 1974). Likewise, sediment retention basins and other erosion control techniques in the semiarid Western United States have been largely ineffective, either because pre-existing geomorphic conditions were disregarded or because of inadequate maintenance (Dortignac and Hickey 1963; Phippen and Wohl 2003; Marston and Dolan 1999). In arid and semiarid catchments, slope, vegetation cover, and soil texture are predictive of soil erosion outcomes (Marston and Dolan 1999; Meeuwig 1970; Blackburn and Skau 1974). Building on this perspective, Gellis et al. (1995, 2001) analyzed erosion control structures in a semiarid catchment characterized by arroyo incision and developed a prioritization framework for restoration within the Zuni Indian Reservation in New Mexico. They highlighted the need for multiscale monitoring to improve understanding of arroyo restoration (Gellis et al. 1995), yet few studies have captured impacts beyond the reach scale.

The primary objective of this study is to monitor stream recovery and restoration in the ephemeral headwaters and intermittent/ephemeral arroyo process domains across multiple spatial scales, and to assess restoration and erosion control



**FIGURE 2** | Study area map of the Southern Plains Land Trust near Lamar, Colorado. Parcel fill colors indicate grazing history, and in-channel restoration structures are shown as dots. Parcels are labeled as (A–G). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.27028)]



**FIGURE 3** | Categorization of rock-based erosion control structure outcomes as (a) not intact, (b) intact but ineffective, not resulting in detectable geomorphic change, and (c) intact and effective, resulting in detectable geomorphic change. Blue arrows indicate flow direction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.27028)]

outcomes in the current restoration zeitgeist. Specifically, this work seeks to: (1) monitor, at the landscape scale, processes sensitive to land-use change, namely soil compaction

and bareness; (2) evaluate how variations in these landscape characteristics, along with basin- and site-scale hydraulic conditions, influence the intactness and geomorphic effects



**FIGURE 4** | Categorization of log-based erosion control structure outcomes as (a) not intact, (b) intact but ineffective, not resulting in detectable geomorphic change, and (c) intact and effective, resulting in detectable geomorphic change. Blue arrows indicate flow direction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]



**FIGURE 5** | Categorization of beaver dam analog (BDA) outcomes as (a) not intact and (b) intact and effective, resulting in detectable geomorphic change. Blue arrows indicate flow direction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

of in-channel restoration structures; and (3) develop a dichotomous key-style decision framework for the Southern Plains Land Trust (SPLT) to guide future placement of in-channel structures.

## 2 | Study Area

Heartland Ranch Preserve (174 km<sup>2</sup>) and Raven's Nest Preserve (19 km<sup>2</sup>), located in Bent County in southeastern Colorado, are the largest preserves managed by the Southern Plains Land

Trust (Figure 2). SPLT began acquiring land at Heartland and Raven's Nest through direct purchase in 2013 and has since continued expanding the preserves. As a result, Heartland has a piecemeal land-use history, with many distinct grazing histories reflecting different stages of cattle removal.

For the purposes of this study, grazing is divided into two categories based on the last presence of large-scale commercial beef cattle grazing operations: historic and recent. Under commercial grazing, the peak annual cattle stocking rate was roughly 0.115 AUM ha<sup>-1</sup>, where one AUM (animal unit month) equals the



**FIGURE 6** | Ineffective log step-fall structure. White outline indicates approximate piping-collapse headcut scarp; blue arrow indicates flow direction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

monthly forage demand by a ruminant weighing 1000 pounds, with or without a calf up to 6 months in age. Land in the “historic” grazing category had cattle removed during or prior to 2015. A second wave of land acquisition and subsequent cattle removal began in 2021; areas designated as having “recent” grazing had commercial operations through at least 2021, with some commercial grazing continuing through 2025.

After the cessation of commercial operations, SPLT reduced the stocking rate to roughly one-tenth of pre-acquisition levels, maintaining about 200 animals—mostly bison—on Heartland Ranch Preserve. Following formal cattle removal, bison herd management by SPLT and occasional trespass grazing have temporarily increased the stocking rate in parts of the preserves, but these are not considered a reactivation of the former commercial grazing regime. The study area and grazing regimes are shown in Figure 2.

The study area lies within a semiarid grassland characterized by flashy hydrology driven by convective summer storms and the North American Monsoon. Annual precipitation at the nearby “Lamar 3” CoAgMET weather station (Schumacher et al. 2018) averages 34 cm/year over 2014–2024. The southern portion of Heartland Ranch features a retreating mesa capped by resistant limestone of the Cretaceous Niobrara Formation. From the mesa scarp region, streams flow generally northward across a dense drainage network underlain by clastic and carbonate sedimentary units of the Cretaceous Colorado Group, Dakota Formation, and Purgatorie Formation (Scott 1968). Mud Creek and Rule Creek are the primary drainage networks within Heartland Ranch and Raven’s Nest, respectively. Their mainstem channels generally fall within the intermittent to perennial incised arroyo

process domain, while smaller tributaries typically represent the ephemeral headwaters process domain. These streams are predominantly alluvial but occasionally interact directly with bedrock. Vegetation cover is dominated by perennial grasses such as buffalograss (*Bouteloua dactyloides*) and blue grama (*Bouteloua gracilis*), along with scattered shrubs and succulent plants, including yucca (*Yucca* spp.) and cholla cactus (*Cylindropuntia* spp.), characteristic of semiarid prairie systems.

### 3 | Materials and Methods

#### 3.1 | Landscape-Scale Analyses

##### 3.1.1 | Soil Compaction

To test the impacts of land use history on soil compaction, we collected soil samples to assess bulk density. Bulk density ( $\rho_b$ ) is defined as the dry weight of soil divided by its total volume, including pore spaces (McKenzie et al. 2002). To collect samples for bulk density analyses, we drove a 7.5-cm-diameter rigid metal cylinder with a sharpened edge into the soil surface and extracted the sample, trimming any roots or material extending beyond the cylinder before placing the material into a sample bag (McKenzie et al. 2002). Samples were collected from surface horizons, which often contained organic material and desiccation cracks.

We sampled within each distinct land-use history of Heartland Ranch Preserve and, within those parcels, across distinct soil types. We grouped soils mapped by the NRCS into four categories based on percent sand: 0%–20%, 20%–40%, 40%–60%, and 60%–80%. Soils with > 80% sand occurred only in one parcel and were therefore excluded, as comparison across grazing histories was not possible. We sampled 10 locations within each soil-texture category and each parcel A–F (see Figure 2), resulting in 238 bulk-density samples. Because SPLT does not manage as much of the upper catchment at Raven’s Nest, the ability to perform catchment-scale monitoring there was more limited than at Heartland. Accordingly, catchment-scale recovery analysis focused primarily on Heartland Ranch, with structure monitoring at Raven’s Nest serving to supplement the evaluation of in-channel responses.

Apart from coverage of each parcel and texture class, sampling locations were otherwise determined in the field by walking 30 paces and dropping the cylinder to identify the next location. We selected starting locations to ensure coverage across the preserve while accounting for the logistical challenges of access and sample transport in SPLT’s remote terrain; most sites were located within 1 km of roads. We recognize that this could introduce some systematic bias toward elevated compaction, since cattle infrastructure (e.g., water tanks, salt sources, and fence lines) is known to influence cattle behavior and was also often located near roads before being removed by SPLT (Ganskopp 2001).

To assess whether grazing history was associated with differences in bulk density across soil textures, we fit a multiple linear regression model with bulk density as the response variable and grazing history, texture class, and their interaction as predictors

(Equation 1). This model tested whether the relationship between bulk density and soil texture varied by grazing history.

$$\text{Bulk density} \sim \text{Texture} \times \text{Grazing} \quad (1)$$

We then used the *emmeans* package in R (Lenth 2025) to compute estimated marginal means and tested pairwise contrasts between parcels with historic and recent commercial grazing within each texture class, evaluating whether bulk density differed significantly between grazing histories for each texture category. All statistical analyses in this study were completed using the R programming language, with significance assessed at the 0.05 level (R Core Team 2025).

### 3.1.2 | Vegetation Cover

We analyzed ground cover across SPLT's Heartland Ranch Preserve using Landsat 8/9 surface reflectance imagery, available beginning in 2013, prior to the establishment of the preserve. For each year from 2013 to 2024, we generated a median composite growing-season (May–September) image in Google Earth Engine and calculated the Bare Soil Index (BSI) to map spatial patterns of bare ground across the preserve (Rikimaru et al. 2002; Gorelick et al. 2017).

$$\text{BSI} = \frac{(\text{SWIR1} + \text{Red}) - (\text{NIR} + \text{Blue})}{(\text{SWIR1} + \text{Red}) + (\text{NIR} + \text{Blue})} \quad (2)$$

BSI (Equation 2) is a good fit for this study because, in vegetated areas (including areas with dead vegetation), near-infrared (NIR) reflectance is significantly higher than shortwave infrared (SWIR1) reflectance, resulting in lower BSI values (Rikimaru et al. 2002; Lillesand et al. 2015). BSI also accounts for differences in the visible bands, recognizing that the red-blue difference tends to be greater for barer pixels. High BSI values are therefore used as an indicator of greater surface bareness across the study area.

We extracted the median BSI for each parcel and year using the *terra* package in R (Hijmans 2025) and fit a multiple linear regression model with median BSI as the response variable and growing-season precipitation, year, grazing history, and the year-grazing interaction as predictors (Equation 3). Growing-season precipitation was calculated as the sum of precipitation over May 1 to September 30 from the “Lamar 3” CoAgMET rain gauge daily precipitation record (Schumacher et al. 2018).

$$\text{Median BSI} \sim \text{Year} \times \text{Grazing} + \text{Precipitation} \quad (3)$$

This model tested whether the temporal trajectory of surface bareness differed among grazing histories, while adjusting for interannual variation in precipitation.

## 3.2 | Project-Scale Monitoring

The specific goals of restoration structures installed at SPLT are varied, including controlling surface erosion, enhancing surface and subsurface water storage, and creating habitat. We broadly classified those placed in ephemeral channels as erosion control structures, as they shared a common mechanism aimed at increasing channel roughness and reducing flow velocity in backwater areas, thereby attenuating fluxes of sediment, water,

wood, and other organic matter. In this analysis, in-channel erosion control and restoration structures were considered distinct only if they address separate problems spanning separate geomorphic contexts. For example, two one-rock dams placed in close proximity beneath the same piping-collapse headcut were grouped as a single structure, whereas two in the same vicinity but associated with distinct headcuts were treated separately.

Using this classification, SPLT installed three beaver dam analogs (BDAs), 24 log-based structures such as post-assisted log structures (PALS) and log step falls, and 65 rock-based structures including one-rock dams (ORDs) and Zuni bowls, for a total of 92 in-channel structures. Structure locations are shown in Figure 2. Of these, 51 were installed within Heartland Ranch Preserve and 42 within Raven's Nest. Only the three BDAs fell within the intermittent to perennial arroyo process domain; the 89 remaining structures were all placed in the ephemeral headwaters.

We documented the type, location, and condition of all distinct stream restoration structures across the study area ( $n=92$ ) using a qualitative field assessment. Structures were first categorized by intactness. For those that were intact, we recorded evidence of geomorphic change. Deposition upstream of and within the interstitial spaces of the structures was the most commonly observed geomorphic change, although avulsion around and scour downstream of structures were also observed. We could not directly estimate the load because the LTPBR structures investigated here are less impervious than retention basins and were often destroyed, leaving an incomplete depositional record (Phippen and Wohl 2003).

Accordingly, we classified structures into three categories: (1) not intact, (2) intact but ineffective, resulting in no detectable geomorphic change, and (3) intact and effective, resulting in geomorphic change. Examples of each outcome across different structure designs are shown in Figures 3–6. Structures categorized as “ineffective” due to their lack of detectable geomorphic response may still provide functional value through flow velocity reduction and energy damping.

One-rock dams (ORDs) are installed perpendicular to flow and constructed, as the name suggests, as one-rock-high features made from locally sourced cobble to small boulder-sized clasts (Figure 3). Figure 3a shows an ORD destroyed during a high-flow event. Figure 3b shows an intact but ineffective ORD, with no sediment deposition in interstitial spaces. Figure 3c shows an effective ORD, where fine-grained fluvial sediment has accumulated within the interstitial spaces between rocks.

Post-assisted log structures (PALS) can take on a variety of forms; at SPLT, they typically feature small vertical stacks of logs or wooden fence posts, secured by posts driven into the channel bed (Figure 4). Figure 4a shows a PALS destroyed during a high-flow event, with only the posts remaining intact. Figure 4b shows an intact but ineffective log structure, trapping windblown vegetation but little sediment. Figure 4c shows an effective log structure, with fluvial sediment deposition visible upstream of the structure.

Beaver dam analogs (BDAs) are typically constructed from packed mud, wood, and other organic material (Figure 5). Figure 5a shows a BDA destroyed during a high-flow event, with

only the posts remaining intact. Figure 5b shows an effective BDA, with extensive upstream fine sediment deposition and cat-tail growth.

Placed within a piping collapse, the log step-fall structure shown in Figure 6 fails to address a subsurface-driven erosion process with surface-based treatment. The absence of deposition within or upstream of the structure indicates that it does not interact with surface flow or fluvial sediment transport; rather, the logs simply cover evidence of the surrounding depression caused by subsurface erosion.

For each structure, we measured the surrounding bank angle using a laser range finder from the bed's break in slope to the top of the adjacent alluvial surface. We recorded local bank vegetation cover (foliar cover), classified as bare (<10% cover), sparse (10%–50%), or heavy (>50%), and noted whether the structure was within three channel widths of a headcut. Whether as a result of piping collapse or surface erosion, headcuts may serve as a point source of sediment that could influence structure outcomes.

We calculated the catchment area upstream of each structure using a 1-m LiDAR-derived DEM and the *whitebox* package in R (Lindsay 2016; Wu and Brown 2022). From the same DEM, we calculated local slope as the average slope over a 10-m upstream distance (Hijmans 2025). Local slope and vegetation cover are more relevant to project-scale outcomes than basin-wide averages because flows are often spatially discontinuous. The Revised Universal Soil Loss Equation (RUSLE) K-factor represents soil erodibility, and we extracted it from the NRCS Web Soil Survey for each restoration structure location (Renard et al. 2017; Soil Survey Staff 2025). Finally, we recorded local grazing history within ~10 m of each structure (historic vs. recent commercial grazing). This variable was strongly associated with the year of installation, as the oldest structures were typically located in areas SPLT acquired and destocked earliest. Grazing history thus also serves as an indicator of structure age. In parcels with historic commercial grazing, most structures were installed during 2021 and 2022, with a few installed as early as 2017. In recently grazed areas, installations occurred after 2022, mostly in 2024.

To understand the factors contributing to the success or failure of restoration structures, we used a multivariate logistic regression model with the odds of intactness as the response variable and bank angle, bank vegetation cover, grazing history, soil erodibility, drainage area, local slope, and proximity to a headcut (Y/N) as predictors. Because drainage area was the only significant predictor, we refitted a simpler univariate model with drainage area as the sole predictor (Equation 4). We excluded the three BDAs from this analysis because their placement within the perennial flow process domain required distinct measurement and analytical techniques from those used for structures in the ephemeral headwaters.

$$\text{Odds of intact structure} \sim \text{Drainage area} \quad (4)$$

We compared the multivariate and univariate models using Akaike's Information Criterion (AIC), which balances model performance against model complexity (Akaike 1998). The

univariate model had a lower AIC score and was therefore selected for further statistical analysis.

Among intact structures, we fit a similar logistic regression model to determine the relative importance of factors contributing to whether a structure produced geomorphic change (Equation 5).

$$\begin{aligned} &\text{Odds that intact structure results in geomorphic change} \\ &\sim \text{Bank angle} + \text{Bank vegetation cover} + \text{Grazing} + K_{\text{factor}} \quad (5) \\ &+ \text{Drainage area} + \text{Local slope} + \text{Headcut indicator} \end{aligned}$$

Because the BDAs produced pronounced and persistent back-water effects and deep pools, we surveyed longitudinal and cross-sectional profiles to qualitatively assess how they altered bed conditions and how site geomorphology contributed to their success or failure.

## 4 | Results

### 4.1 | Landscape-Scale Analyses

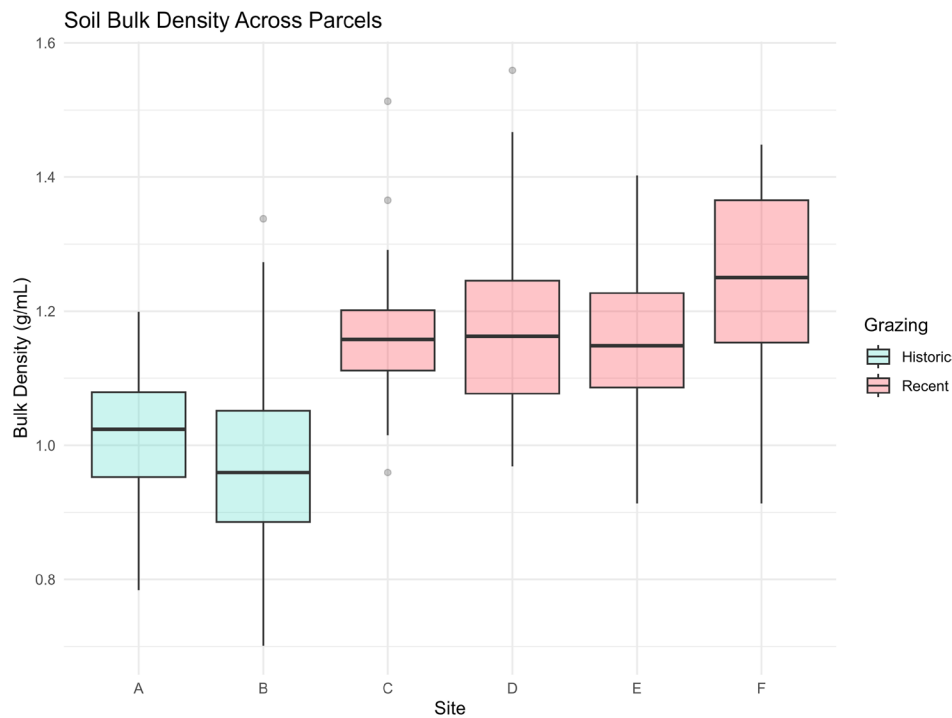
#### 4.1.1 | Soil Compaction

Soil bulk density ( $\rho_b$ ) is significantly higher in parcels with recent commercial cattle grazing (>0.115 AUM ha<sup>-1</sup>) compared to parcels with light (~0.01 AUM ha<sup>-1</sup>) bison/cattle pressure, controlling for background soil texture ( $p < 0.0001$ ). Figure 7 depicts the measured bulk density distribution across parcels A-F.

We performed a contrast *t*-test on estimated marginal means to test whether soil bulk density in parcels without recent commercial grazing (A, B) differs from those with recent heavy grazing (C, D, E, F) within each soil-texture class. Regardless of soil composition, recently grazed parcels were more compacted ( $p < 0.0001$ ). The two sandiest classes exhibited larger differences in compaction by grazing history (0.232 and 0.192 g/mL) compared to finer texture classes (0.179 and 0.153 g/mL). Overall, these results suggest that grazing history is a strong predictor of soil bulk density.

#### 4.1.2 | Vegetation Cover

The trajectory of growing-season composite BSI is highly variable through time, with some years showing markedly higher vegetation cover. This pattern is expected, as vegetation in semiarid ecosystems is highly dependent on precipitation, which itself exhibits strong interannual variability driven by the North American Monsoon, the distribution of regional and mesoscale precipitation events, and localized convective storms. To account for this variability, we included precipitation as a covariate in the model presented in Equation (3). The trajectory of soil bareness through time is not dependent on grazing history but is strongly and inversely associated with growing-season precipitation ( $p < 0.0001$ ). These suggest that recent grazing management has not had a significant effect on vegetation cover.



**FIGURE 7** | Measured soil bulk density (g/mL) across different parcels within SPLT's Heartland Preserve. Parcels with recent heavy cattle grazing are shown in red, and those with historic grazing in blue. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rca.20128)]

## 4.2 | Project-Scale Monitoring

Restoration structure outcomes across the SPLT's Heartland Ranch and Raven's Nest Preserves are shown in Figure 8i–iv. In total, 22 (24%) erosion control (e.g., Zeedyk structures, PALS) structures were destroyed, 42 (46%) were intact but resulted in no detectable geomorphic change, and 28 (30%) were intact and geomorphically responsive. One of the three distinct BDAs (33%) was destroyed; the other two (67%) were intact and geomorphically responsive.

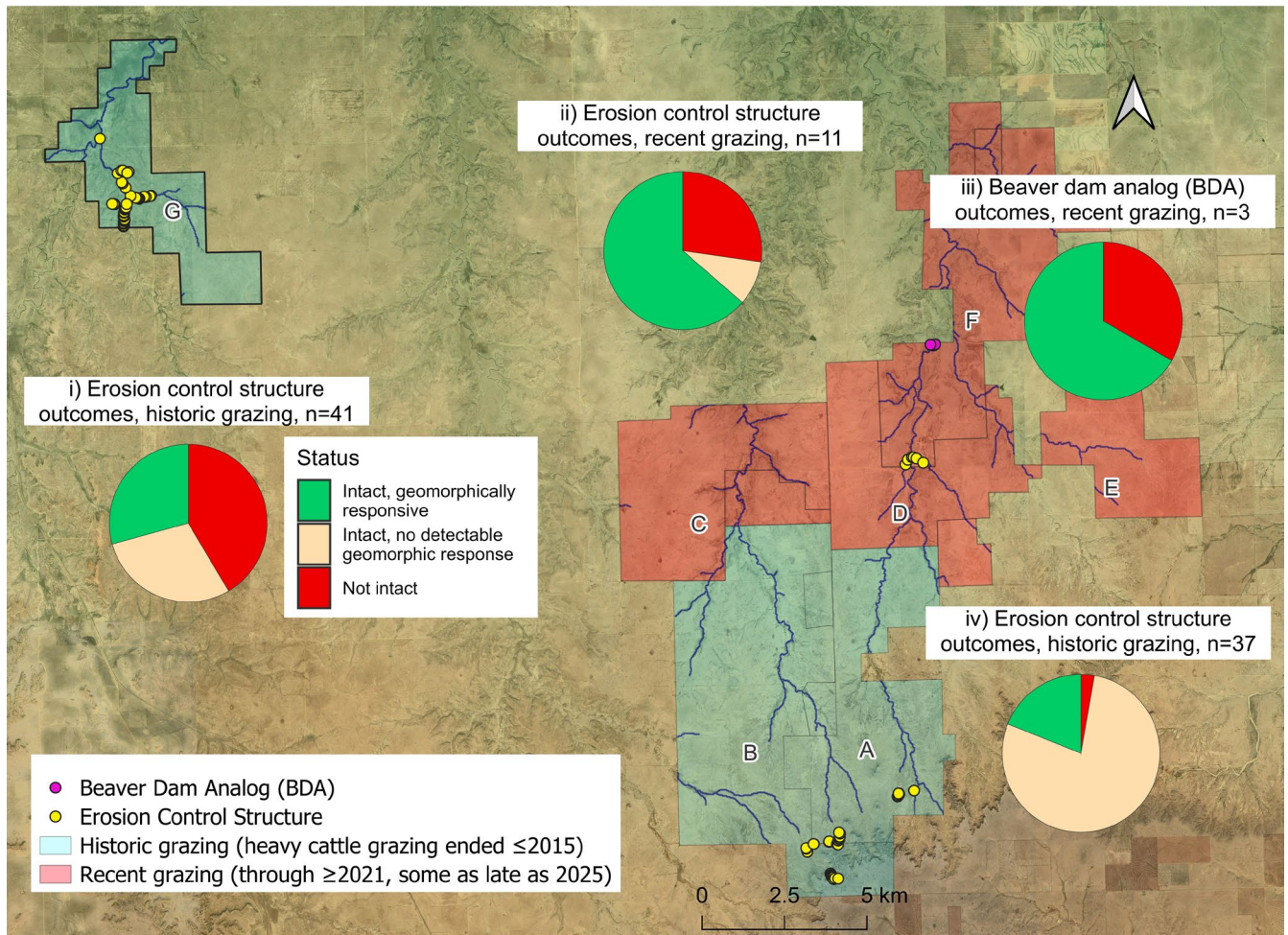
The spatial distribution of structure outcomes shown in Figure 8 reveals a clear drainage-area control, with structures located in the headwaters just north of the mesa mostly intact but producing little geomorphic change. Farther downstream, fewer structures remain intact, but more have trapped sediment, resulting in their classification as intact and geomorphically responsive. Grazing history also appears to influence restoration outcomes: structures on Raven's Nest Preserve (Figure 8i) were less effective than those in downstream portions of Heartland Ranch (Figure 8ii), despite similar positions within the drainage network and an older installation date (2021–2022). The structures in Figure 8ii were installed in more recently grazed areas and have had less time (since 2024) to interact with flows.

This trend is confirmed in an analysis of the results from the multivariate logistic regression models presented in Equations (4) and (5). Each additional km<sup>2</sup> of drainage area is associated with, on average, 6.6% lower odds of structure intactness ( $p < 0.0001$ ). Conversely, among intact structures, each additional km<sup>2</sup> of drainage area is associated with, on average, 11% higher odds of geomorphic change ( $p = 1.49 \times 10^{-3}$ ).

The results of the multivariate logistic regression model presented in Equation (5) are shown in Table 1. Some logistic regression odds ratios are extreme with wide confidence intervals, particularly the ratio associated with slope, because a one-unit change in slope is far larger than the observed range (roughly 0–0.1). Extreme values may also reflect a small sample size ( $n = 92$ ) and multicollinearity. Aside from drainage area, higher local slope, sparse (<50%) bank vegetation cover, and recent commercial grazing each increased the odds that an intact structure produced geomorphic change, when controlling for all other variables in the model (Table 1).

The competing effect of drainage area on restoration outcomes is shown in Figure 9, which plots the odds of structure intactness and structure-induced geomorphic change versus drainage area. Structure intactness decreases exponentially, but structure-induced geomorphic change increases exponentially with increasing drainage area. The large uncertainty band associated with the geomorphic change line reflects the additional controls exerted by slope, bank vegetation, and grazing history, whereas intactness is primarily a function of drainage area.

The small BDA sample size ( $n = 3$ ) makes statistical modeling ineffective for identifying factors contributing to restoration outcomes. All three BDAs were installed along a deeply incised, low-gradient section of Mud Creek with perennial flow and an upstream catchment area of ~82 km<sup>2</sup>. The valley bottom here is densely vegetated with sedges and grasses, and all sites fall within the “recent” commercial grazing regime (Figure 5). Two BDAs remained intact and produced extensive upstream backwater and fine sediment deposition, while the third failed. The failed structure was located in a slightly more confined reach



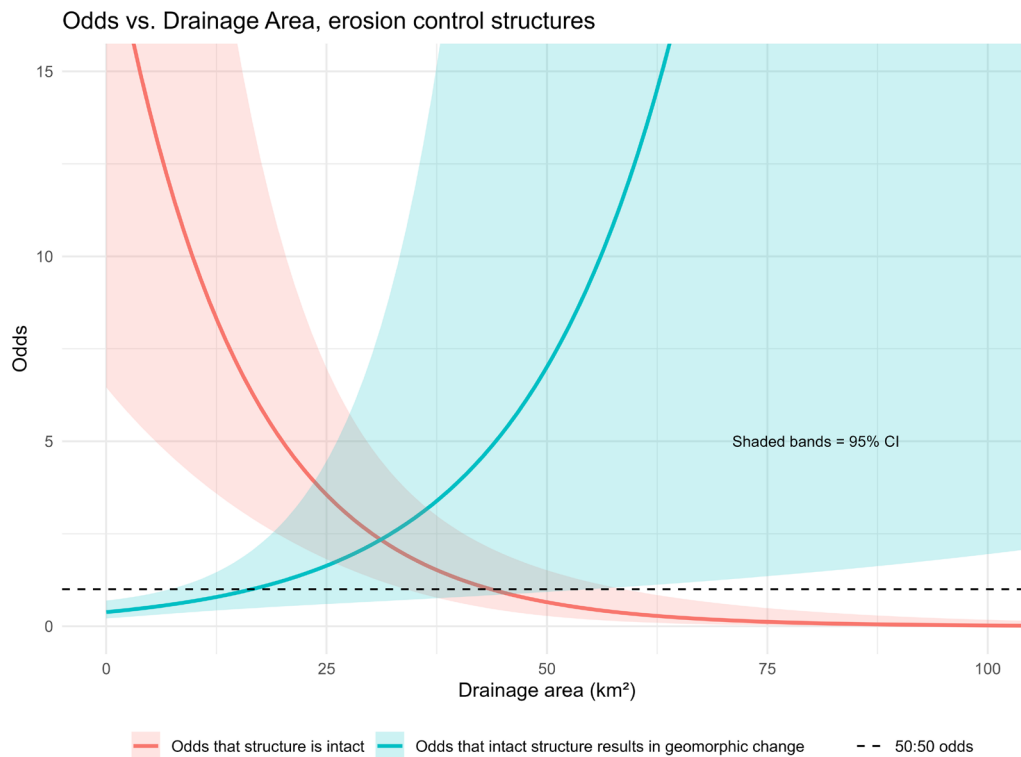
**FIGURE 8** | Erosion control and beaver dam analog (BDA) outcomes across different geomorphic settings (i–iv). Parcels are labeled (A–G). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.20120)]

**TABLE 1** | Outcomes of multivariate logistic binary regression analysis, examining the influence of various basin and local characteristics on the odds that an erosion control structure resulted in geomorphic change.

| Predictor                         | Odds ratio            | 95% CI                                    | p                     |
|-----------------------------------|-----------------------|-------------------------------------------|-----------------------|
| Drainage area (km <sup>2</sup> )  | 1.11                  | (1.05, 1.19)                              | $1.49 \times 10^{-3}$ |
| Local Slope (m/m)                 | $5.45 \times 10^{15}$ | $(1.91 \times 10^3, 6.70 \times 10^{32})$ | $4.37 \times 10^{-2}$ |
| Bank Angle (degrees)              | 0.991                 | (0.948, 1.03)                             | 0.665                 |
| RUSLE K-factor                    | 7.56                  | $(5.40 \times 10^{-3}, 1.32 \times 10^4)$ | 0.582                 |
| Recent Grazing (vs historic)      | 32.2                  | $(2.63, 1.14 \times 10^3)$                | $1.84 \times 10^{-2}$ |
| Near headcut (vs not)             | $9.64 \times 10^{-2}$ | $(6.07 \times 10^{-3}, 0.783)$            | $5.43 \times 10^{-2}$ |
| Bare bank vegetation (vs heavy)   | 42.5                  | $(1.90, 2.47 \times 10^3)$                | $3.51 \times 10^{-2}$ |
| Sparse bank vegetation (vs heavy) | 0.996                 | (0.141, 6.08)                             | 0.996                 |
| Blue: significant, > 1            |                       | Red: significant, < 1                     |                       |

with a steeper average bank angle (21°) compared to ~10° for the successful BDAs. This confinement likely increased flow depth and velocity during high flows, amplifying the shear and normal stresses on the structure that ultimately contributed to its destruction.

These results indicate that, within the ephemeral headwaters, structures placed higher in the catchment—within piping-dominated areas of low drainage area—were unlikely to produce geomorphic change. In contrast, structures located farther downstream in zones of episodic surface flow were more likely



**FIGURE 9** | Odds of erosion control structure intactness (red) and structure-induced geomorphic change (blue) as a function of drainage area ( $\text{km}^2$ ). Shaded regions show 95% confidence bands. A dashed black line indicates 50:50 odds. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.270128)]

to capture material, particularly where gradients were high and vegetation was sparse. In areas of perennial flow, the success of BDAs depended primarily on bank morphology, namely bank angle and degree of confinement.

## 5 | Discussion

### 5.1 | Landscape-Scale Recovery

Upland response to cattle grazing is not uniform. Bulk density responded within 10 years, as indicated by consistent differences in bulk density in relation to grazing history. Although parcels C–F differ slightly in acquisition history and cattle were removed at various times between 2021 and 2025, all still exhibit elevated bulk density compared to parcels A and B, which have experienced only light, non-commercial, bison-dominated grazing since 2015 (Figure 7). This suggests that the threshold for measurable recovery of soil structure in this semiarid grassland system exceeds 4 years and is likely on the order of a decade. Consistent with this interpretation, previous studies of hydrologic recovery in Colorado grasslands found that infiltration rates required roughly 13 years to return to pre-disturbance levels (Branson et al. 1981; Dortignac and Love 1961).

In contrast, vegetation cover did not respond within 10 years of cessation of cattle grazing. Previous studies indicate that, at landscape scales, even intensive rotational or other managed grazing systems may not produce significant increases in vegetation cover relative to non-rotational practices (Venter et al. 2019; Briske et al. 2008; Hawkins 2017). While grazing management at SPLT is not rotational but rather represents a step reduction in

stocking rate, the underlying principle is similar: remove livestock to allow vegetation to recover. The BSI signal, however, implies high vegetation cover during wet years but no difference in the grazed versus ungrazed temporal soil bareness trajectory after accounting for background precipitation. This trend suggests that interannual changes in remotely sensed ground cover are dominated by annual plant growth or background soil moisture rather than persistent increases in perennial cover following grazing reduction.

Several explanations may account for the observed similarity in vegetation cover among parcels with different grazing histories. One possibility is that grazing occurred below the landscape's carrying capacity and therefore did not significantly affect vegetation cover (Venter et al. 2019). A second possibility is that vegetation cover was diminished long ago and has not yet recovered. Given the long (> 100 years) commercial grazing history at SPLT and the ubiquity of grazing in adjacent areas, pre-grazing conditions are unknown and the complete grazing chronology is uncertain beyond the years immediately prior to acquisition by SPLT. It is therefore possible that the similarity in vegetation cover relative to recently grazed parcels instead reflects a lack of recovery. Mechanistically, desiccation cracking provides a plausible explanation for this persistent legacy: field experiments have shown that in shrink-swell clay soils like those at SPLT, grazing-induced structural damage promotes extensive cracking, whereas ungrazed soils experience shrink-swell cycles without surface rupture (Reid and Parkinson 1984). Once cracks form, precipitation infiltrates rapidly through the topsoil into deeper layers, potentially preventing vegetation recovery for decades and perpetuating the legacy of historic grazing (Reid and Parkinson 1984).

A third possibility is that vegetation recovery is occurring, but at different timescales across the landscape. In the Great Basin, Fesenmyer et al. (2018) documented increases in remotely sensed riparian vegetation condition (NDVI) within 3 years of implementing grazing exclosures and conservation-oriented grazing. Recovery in those systems was measured near channels and dominated by woody species such as willow, often facilitated by subsequent beaver colonization and dam-building activity. Although the vegetation composition of the Great Basin differs markedly from that of the Great Plains, these results demonstrate that, in a semiarid environment, riparian vegetation recovery can occur relatively quickly under favorable grazing management. At SPLT, however, any such localized response is overshadowed by the absence of measurable change in grassland vegetation across the broader landscape, which appears to be changing on timescales longer than have been observed thus far following grazing cessation.

Further, perennial grass recovery in semiarid uplands may manifest as changes in root biomass, basal cover, or changes in species composition—none of which are detectable by BSI. The BSI analysis here indicates that, on a landscape scale, there is no large-scale signal of year-to-year aboveground recovery after controlling for precipitation. The remote methods used here likely did not capture recovery at the patch, plant, riparian, or subsurface scales.

## 5.2 | Project-Scale Outcomes

In small drainage areas, erosion is dominated by subsurface piping collapse, so restoration structures typically remain intact but experience little surface flow to transport sediment. In larger drainage areas, erosion results from the combined effects of subsurface and surface processes; flash floods may destroy structures, yet those that remain intact may trap sediment, particularly in steep, sparsely vegetated, and recently grazed reaches (Figure 9; Table 1). Essentially, structures are most geomorphically responsive where they intercept high sediment loads. This relationship aligns with prior studies showing that steep, sparsely vegetated reaches in semiarid landscapes contribute disproportionately to sediment flux and that hard-engineered erosion control efforts are often ineffective when these fundamental drivers are overlooked (Phippen and Wohl 2003; Marston and Dolan 1999). The outcomes of LTPBR, Zeedyk, and NIDS restoration structures are no different; the geomorphic response is governed primarily by context rather than intervention type (Wohl et al. 2024).

The influence of grazing history on restoration outcomes suggests a nonlinear, two-phase recovery trajectory analogous to those observed following dam removals and other disturbances (Fields et al. 2025; Pizzuto 2002). The first phase, operating over short timescales, involves rapid adjustment of intrinsic channel properties—such as width, depth, and grain size at the transect scale—to prevailing hydrologic conditions. The second phase, occurring over longer timescales, involves adjustments of extrinsic properties at the reach-to-landscape scale, including hillslope morphology and sediment-supply processes (e.g., soil piping, surface erosion) that are driven by changing boundary conditions such as land use, extreme flows, climate, subsidence, uplift, and geology (Fields et al. 2025; Schumm 1973, 1979).

Despite comparable positions within the catchment and later installation, structures in the recently grazed northern portion of Heartland Ranch Preserve were more likely to exhibit geomorphic change (64%) than those at Raven's Nest Preserve (29%; Figure 8i–ii). Most structures within Heartland's northern parcels were installed in 2024, shortly after the end of commercial grazing in 2023. Residual soil compaction and subsequent surface erosion at these sites allowed ordinary flows to mobilize and deposit sediment, temporarily lowering the effective precipitation and effective discharge (Wolman and Miller 1960; Schumm 1979). The deposits behind restoration structures therefore reflect transect-scale channel adjustment rapidly modulated by the prevailing hydrology.

We infer that ordinary flows no longer produce significant sediment transport to the structures over longer timescales. In long-rested areas, adjustment is governed primarily by extrinsic alterations to boundary conditions beyond the channel, driven by land use, climate, vegetation, and extreme events rather than by ordinary flows (Fields et al. 2025). In this system, relevant extrinsic controls include the reduction of soil compaction through time (Figure 7), which limits overland flow and surface erosion, and episodic large floods capable of destroying restoration structures. Most structures at Raven's Nest Preserve were installed during 2021–2022, long after the end of commercial grazing in 2013. Consequently, the higher proportion of destroyed structures (41%) and the lower proportion that produced geomorphic change (29%) at Raven's Nest likely reflect this shift to a lower-compaction, low-sediment, flood-driven recovery regime rather than a difference in design efficacy (Figure 8i).

Finally, these findings raise a broader question: to what extent can structure-based restoration in grassland systems be considered truly process-based? In this study, only about 30% of LTPBR erosion-control structures were both intact and produced detectable geomorphic change. The philosophy behind LTPBR recognizes the potential for multiple drivers of stream degradation (Wheaton et al. 2019). However, as commonly implemented, LTPBR assumes that the dominant process disruption is a decline in the spatial frequency of natural in-channel obstacles to flow resulting from large wood loss, channel straightening, and beaver extirpation (Beardsley 2024), or so-called structural starvation. Structural starvation is a common impairment, and where this assumption holds, process-based restoration should focus on re-establishing persistent, self-sustaining log jams, beaver dams, and other sources of in-channel heterogeneity. However, in fine-grained, wood-poor grassland systems, the introduction of coarse material (e.g., one-rock dams, Zuni bowls) and large-wood analogs (e.g., PALS, log step-falls) does not align with the dominant geomorphic processes. Although some restoration manuals acknowledge that structural starvation is not universal (Wheaton et al. 2019), the widespread appeal of LTPBR has encouraged a one-size-fits-all approach that often overlooks the processes governing channel adjustment (Nash et al. 2021; Wohl et al. 2024).

## 5.3 | Restoration Decision Framework

Based on our field observations and data analyses at the Southern Plains Land Trust preserves, we developed a decision

**TABLE 2** | Southern Plains Land Trust stream restoration decision framework.

| Southern Plains Land Trust stream restoration decision framework                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (1) Is there a specific management problem caused by a physical process?<br>No: Do not install in-channel structural interventions.<br>Yes: Go to (2).                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| (2) Is there active grazing or another land use disturbance resulting in compaction, reduced vegetation cover & elevated sediment yield (e.g., roads, drill pads)?<br>No: Go to (4).<br>Yes: Go to (3).                                                                                                                                                                                                                                                                                                                                                                                                             |
| (3) Can you address the underlying cause of the compaction disturbance (e.g., remove cows, decommission and rip roads)?<br>No: Do not install in-channel structural interventions. Structures are not self-sustaining, and an ongoing land use disturbance may quickly deplete structural sediment storage. Structures only temporarily alleviate symptoms if the disturbance is ongoing.<br>Yes: Address disturbance, return to (1).                                                                                                                                                                               |
| (4) Is drainage area $< 16 \text{ km}^2$ and is geomorphic change dominated by subsurface soil piping collapse?<br>No: Go to (5).<br>Yes: Do not install in-channel structural interventions. Surface structures do not prevent subsurface-driven erosion and are ineffective at stabilizing such headcuts; they should not be installed in close proximity to them. Instead, structures are better suited to portions of the channel dominated by surface flow and located sufficiently far downstream from active headcuts, where they can enhance natural bank angle reduction and vegetation recolonization.    |
| (5) Is drainage area $> 44 \text{ km}^2$ (large discharge, high shear stress)?<br>No: Go to (7).<br>Yes: Erosion-control structures (e.g., PALS, ORDs, Zuni bowls etc.) are unlikely to stay intact. Go to (6).                                                                                                                                                                                                                                                                                                                                                                                                     |
| (6) Is there perennial flow?<br>No: Do not install in-channel structural interventions.<br>Yes: If banks are shallow ( $\sim 10^\circ$ ) and vegetation has heavily encroached into the already-widening arroyo channel (Schumm et al. 1984), BDAs may enhance natural stabilization and promote additional water storage and vegetation growth.                                                                                                                                                                                                                                                                    |
| (7) Did the compaction disturbance end $\leq 10$ years ago?<br>No: Do not install in-channel structural interventions. Bulk density and infiltration have likely recovered and there is less disturbance-enhanced erosion and sediment yield.<br>Yes: Consider structural intervention, while recognizing that coarse material and large-wood analogs are not likely to be self-sustaining and may not align with the dominant geomorphic processes operating in grasslands stream corridors. Target areas with high sediment yield; these may be areas with relatively high slopes and low local vegetation cover. |

framework that can be used to evaluate the potential efficacy of future restoration structures when sites and methods of stream restoration are being considered (Table 2). The quantitative thresholds for drainage area and time since grazing ceased are specific to this field area, but the general approach should be applicable to other semiarid grasslands that exhibit both piping and surface erosion as sources of channel formation and modification. In other words, comparable frameworks could be developed for other semiarid grasslands, recognizing that specific numeric thresholds will vary with topography, hydrology, geology, soil texture, vegetation, land use, and disturbance history.

The decision steps in Table 2 reflect our observations that, in the study area, (i) structural interventions in close proximity to an active headcut generated by piping are not effective and (ii) erosion-control structures are unlikely to remain intact in ephemeral channels with large contributing areas.

## 6 | Conclusions

In this study, we conducted multiscale monitoring of post-grazing recovery and restoration outcomes in semiarid

grassland headwater channels, spanning transect to landscape scales. The Mud and Rule Creek catchments and adjacent land managed by the Southern Plains Land Trust (SPLT) in southeastern Colorado served as a case study for this work, although the general patterns observed are likely representative of similar semiarid grassland systems elsewhere. We examined landscape-scale recovery of soil compaction and vegetation cover following cattle removal, finding that the two are out of sync. Soil bulk density was significantly lower in parcels that had rested for roughly a decade compared to those rested for less than 5 years, whereas changes in remotely sensed upland vegetation cover were comparable among grazing histories.

We also evaluated the geomorphic factors controlling the intactness and geomorphic effectiveness of in-channel restoration structures, finding that success depends strongly on geomorphic context. In channels draining small catchments, erosion is dominated by subsurface piping collapse; structures typically remain intact but trap little sediment because surface flow is minimal. In larger catchments, flash floods may destroy some structures, but those that remain intact are more likely to trap sediment—especially in steep, sparsely vegetated, and recently grazed reaches. Thus, structure intactness primarily reflects the

flow regime, while the geomorphic impacts of in-channel restoration structures primarily reflect local sediment supply.

We hypothesize that post-grazing recovery follows a nonlinear trajectory: an early phase of rapid, transect-scale adjustment to prevailing hydrology gives way to longer-term, reach- and landscape-scale adjustments governed by extrinsic controls such as decompaction and extreme events. To guide future restoration efforts at SPLT, we developed a simple dichotomous key that could be adapted for other semiarid grassland systems. As in any landscape, truly process-based restoration must identify and address the geomorphic processes driving channel adjustment, whether soil piping, surface erosion, or beaver activity, rather than rely on generic structural templates.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

Processed data used for the linear and logistic regression analyses are publicly available on Dryad (an open-access data repository) and have been assigned the DOI <https://doi.org/10.5061/dryad.4b8gthtsp>. The dataset also includes links to a GitHub repository containing all analysis code and instructions for accessing the raw data.

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